RECENT DEVELOPMENTS IN AGGREGATE RESEARCH

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by

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TO: K. B. Woods, Director
Joint Highway Research Project

July 13, 1962

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 5-1

Attached is a paper entitled "Recent Developments in Aggregate Research" by Professor J. F. McLaughlin of our staff. The paper has been prepared for presentation by Professor McLaughlin at the IV World Meeting of the International Road Federation in Madrid, Spain, in October 1962.

The paper summarizes recent developments in the following areas of aggregate research:

1. The influence of physical characteristics of aggregates on the frost resistance of portland cement concrete.

2. Degradation of aggregate.

3. Chemical reaction of aggregate in portland cement concrete.

4. The role of aggregate in the skid-resistance of highway pavement surfaces.

A major portion of the research discussed has been that conducted by the Project at Purdue University.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

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Attachment

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RECENT DEVELOPMENTS IN

AGGREGATE RESEARCH

By

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are highly reactive rather than inert." They state further that knowledge of the "several forms of activity is essential to the intelligent evaluation of a given aggregate source as a concrete making material." This reasoning may be extended into the evaluation of aggregates for bituminous mixtures, where the preferential affinity of an aggregate for asphalt or water is an important consideration in the selection of suitable materials. These are but two examples, many others could be given in support of the statement that aggregates are not inert materials of construction.

A broader definition of the term mineral aggregate was stated by Woods (3) as follows:

> "An aggregation of sand, gravel, crushed stone, slag, or other material of mineral composition, used in combination with a binding medium to form bituminous and portland cement concrete, macadam, mastic, mortar, plaster, etc., or alone as in railroad ballast, filter beds and various manufacturing processes such as fluxing, etc."

This is a less restrictive definition and covers the full scope of aggregate usage in highway construction.

Aggregate particles possess a series of physical and chemical properties which, together with grading, determine the suitability of the aggregate for an engineering application. An understanding of these properties is essential as a basis for development of empirical tests, for establishing specification limits based upon such tests, and, in general, for evaluation and selection of aggregates for use under specific conditions of service (4). Current research in the aggregate field attempts to improve this understanding. One could no doubt classify the areas of research in various ways but for the purpose of discussion in this paper research in the following categories is considered:

1. The influence of physical characteristics of aggregates on the frost resistance of portland cement concrete

2. Degradation of aggregates

3. Chemical reactions of aggregate in portland cement concrete

4. The role of aggregate in the skid-resistance of highway pavement surfaces

These categories are not intended to include all research in this field but rather to cover a few of the subjects that are of primary interest to highway engineers. In this paper an attempt has been made to give broad coverage to current developments in two of the four research areas that have been enumerated. The role of aggregates in skid-resistance of highway pavement surfaces and the influence of aggregates on the durability of concrete in freezing and thawing are given more detailed treatment since these subjects have been dealt with extensively in research projects conducted at Purdue University under the direction of personnel of the Joint Highway Research Project of the School of Civil Engineering.

THE INFLUENCE OF PHYSICAL CHARACTERISTICS OF AGGREGATES ON THE FROST RESISTANCE OF CONCRETE

The resistance of concrete to deterioration caused by freezing and thawing has been the subject of many investigations. In 1945, Powers (5) suggested an explanation or hypothesis for the action of frost on concrete taking into account such factors as the degree of saturation of the concrete, the permeability and strength of the concrete, hydraulic pressures generated during freezing, and air-filled cavities. This work, a later study by Powers (6), and numerous other contributions have, from the standpoint of the highway engineer, adequately described the situation for cement paste and have proven the effectiveness of air entrainment in providing a high order of durability to concretes made with good quality aggregates.

Verbeck and Landgren (7) state that the same general concepts that have successfully provided an understanding of the frost resistance of cement paste are also applicable to aggregates. They present the case as follows:

> "Aggregates may cause disruption of concrete by the generation of high destructive hydraulic pressures during freezing. By analogy with paste, the magnitude of the hydraulic pressure developed in aggregates depends upon their degree of saturation (proportion of total void space filled with water) and the permeability and size of the aggregate particle. Furthermore, if the degree of saturation of the aggregate is sufficiently high (above the "critical," 91.7 per cent) so that the remaining air-filled void space cannot accommodate the 9 per cent expansion of water during freezing, then water will be expelled into the paste surrounding the aggregate particle and potentially destructive hydraulic pressures may develop there as well as in the aggregate. Thus, the properties of paste, its permeability, air content, and porosity, are also involved in the problem of aggregate durability. In addition, the paste can significantly influence the degree

of saturation of the aggregate in concrete by limiting the ingress of water; the protection afforded in this manner depends upon the permeability and thickness of the paste or mortar cover separating the aggregate from the wet surface of the concrete.

"A more detailed consideration of the various mechanisms by which the various physical characteristics of the aggregate and of the paste can influence the durability of the concrete reveals that the effects of some of these characteristics are closely interrelated and that some may have several and perhaps opposing effects.

"Analysis of the mechanisms is considerably simplified by separating the over-all problem into two distinct aspects within which the individual roles of the pertinent physical characteristics of the aggregate and the paste can be developed more clearly. These major aspects and the important factors involved are as follows:

1. The time required for an aggregate to become critically saturated when in concrete exposed to water as influenced by:

   a. Pore size and porosity of aggregate.

   b. Thickness and permeability of protective mortar cover.

2. The various phenomena in the freezing of fully saturated aggregate demonstrating:

   a. Elastic accommodation by aggregate.

   b. "Critical" size of aggregate (internal hydraulic pressures).

   c. Influence of confining mortar (external expulsion distance and external hydraulic pressures).

   d. The influence of various factors modifying these effects of freezing, that is, soluble materials, degree of saturation and freezing point depression in fine aggregate pores."

Verbeck and Landgren then considered in detail these various phenomena, introducing supporting experimental data where appropriate. They concluded in part that the influence of aggregates on the durability of concrete depends upon the physical characteristics of the aggregates and certain properties of the mortar component. Concerning test methods commonly employed to evaluate the potential durability of aggregates for concrete, they concluded that certain of these are frequently inappropriate and misleading as regards actual field performance of the concrete.*

Other investigators have paid special attention to measurements of the pore structure of aggregates since this has been shown to have an important influence on the durability of concrete (8) and said by some to be perhaps <u>the most important</u> of all the physical properties of a concrete aggregate (9).

Dolch (10) recently reported a study made for the purpose of investigating certain limestone coarse aggregates by means of fluid-flow experiments and to attempt to relate the data to properties of the material, to observed field performance, and to hypotheses concerning movement and freezing of water in concrete. He outlined the approach used in the investigation as follows (11):

> "Aggregates with both good and poor field performance were chosen. The quarries were sampled. Small rectangular prisms were shaped from the rock and their dimensions were measured. True density, porosity, and bulk density were determined. Permeability to air was measured in a pressure-decay apparatus at various pressures and the slip correction was determined. The absorptivity coefficient was measured by capillary absorption on a free-water surface. Tortuosity was determined by the electrical analog method. Specific surface was determined by the sorption method using water vapor. These data were then used to calculate characteristics of the pore system on the basis of a simple model."

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* The results of a comprehensive study of the four ASTM methods of test for resistance of concrete specimens to freezing and thawing are reported in <u>Special Report No. 47</u> of the Highway Research Board titled, "Report on Cooperative Freezing and Thawing Tests of Concrete," 1959. Thirteen laboratories throughout the United States and Canada participated in the investigation. Three concrete mixtures were used involving two coarse aggregates known from field performance records to be of good and poor quality respectively. It was concluded that the four ASTM test methods (C 290, 291, 292 and 310) provide useful procedures for comparing the relative durability of different concretes within a given laboratory. Wide variation of test results for concretes of intermediate durability appears to be a normal characteristic of the methods. The data were not sufficient to permit recommending a single test method for all purposes.

A principal conclusion of this investigation concerned the delineation of aggregates susceptible to frost damage by reference to derived ratios indicating materials that will become saturated rapidly when exposed to free water. As stated by Dolch:

> "The rate of increase of the degree of saturation of a material when exposed to free water, as measured by the ratio K_a: $2\epsilon^2$ (where K_a is a measure of absorptivity in sq cm per sec and ϵ is porosity), and the ratio of the absorptivity to the permeability are two indices of frost susceptibility.......... The more susceptible materials can be expected to have comparatively large values of both these ratios."

Pore size distribution of some carbonate aggregates was measured by Hiltrop and Lemish (12) by use of a mercury capillary pressure apparatus to see if this factor of the aggregate could be related to the frost resistance of concrete. They concluded that pore size distribution alone was not closely related with either laboratory freezing and thawing resistance or field service record of concrete made with the aggregates they investigated.

Deleterious Substances in Concrete Aggregates

The presence of certain rocks, minerals, and other substances can greatly impair the quality of concrete made with aggregates containing only small percentages of these materials. The terms "deleterious substances" or "deleterious constituents" have become common for describing this class of materials.

Deleterious substances can be categorized on the basis of their harmful effects (13). The most harmful class consists of those that tend to expand from strains induced by weathering and disrupt the concrete. The most common examples of this class are porous cherts, well-indurated clays, and limestones containing expansive clays. Such materials, when frozen in a saturated or near saturated condition or, in some cases, when merely exposed to water, undergo volume change accompanied by the development of sufficient pressure to cause deep-seated disintegration of the concrete.

Research on these materials and the problems they create has been continuous, with the result that much is known concerning general characteristics of the materials, test methods to detect them, and processing methods to remove them (14). Specifications for concrete aggregates commonly limit shale, lightweight chert, etc. to small percentages with recognition being given to such factors as exposure, maximum aggregate size, effects of "sweetening", etc. (15).

A recent study by Schuster and McLaughlin (16) attempted to fill-in some gaps in knowledge concerning the basic properties of cherts and shales and to determine how these properties (and hence their effect on concrete durability) might differ for materials from different regions within a given geographic area. They suggested that such knowledge, combined with previous findings is necessary for the development of realistic specifications for concrete aggregates.

The investigation was primarily a study of the durability of concrete produced by combining small percentages of chert or shale with a single fine aggregate, crushed stone coarse aggregate and portland cement. Both the fine and coarse aggregate had good service records. In addition to the durability testing, tests were conducted to determine many of the basic physical properties of the deleterious materials in order to develop possible relationships between these properties and durability. The cherts and shales were obtained from several gravel sources throughout the State of Indiana and these were the only components of the gravels that were studied. Except in a general way, no attempt was made to determine from which geologic formations the gravel aggregates originated.

The complete study is detailed in reference (16) and to outline its many parts is beyond the scope of this paper. However, the conclusions reached by Schuster and McLaughlin are of interest. These were:

1. Chert exhibits a definite relationship between its bulk specific gravity and durability in concrete exposed to freezing and thawing. Apparently only chert with a bulk specific gravity of less than 2.45 (saturated surface-dry basis) will cause either deep-seated or surface deterioration of air-entrained concrete in which it is used.

2. For a wide variety of cherts, the source of the chert has no effect on its freeze-thaw durability in concrete.

3. The freeze-thaw durability of concrete containing chert apparently is not as dependent on pores in the chert less than 5 microns in diameter as has been postulated by others. Instead, chert durability is apparently based on a more complicated interrelationship between total porosity, size of pores, absorption and degree of saturation. Pores larger than the 5-micron size permit easier passage of water into immersed aggregates, result in relatively high degrees of saturation, and contribute to freeze-thaw deterioration of lightweight chert. Microscopic studies of polished sections show that these larger pores make up about half the void volume in 2.45 minus specific gravity chert.

4. The petrographic characteristics of the cherts influence the freeze-thaw durability of these materials only in the relationship of these characteristics to porosity of the cherts. For example, although

mineralogy of the cherts has no direct effect on their freeze-thaw durability, the presence of carbonate rhombs, which have weathered out to form voids, has lessened the durability of some chert particles.

5. Many shales will not cause deep-seated deterioration of air-entrained concrete beams subjected to laboratory freezing and thawing when included in these beams in amounts up to ten per cent. The inherent structural weakness of these materials may account for this.

6. Different shales cause considerably different degrees of surface deterioration of air-entrained concrete exposed to freezing and thawing. Some shales cause considerable popout damage when included in concrete in amounts as low as two per cent of the coarse aggregate. Other shales cause little damage when used in amounts up to ten per cent.

7. The durability of the shales studied apparently was related primarily to the porosities and absorptions of these materials; the most porous and most absorbent causing the greatest amount of surface deterioration of concrete in which these materials are used. However, the strength and induration of the shales, as determined by relative amounts of clay minerals and detrital quartz present, also influence the ability of these materials to cause surface deterioration, the softer, weaker materials being less resistant than the harder, stronger ones.

8. As theorized by Powers (6), concretes with air-void spacing factors lower than 0.01 inches are well-protected from freezing-and-thawing deterioration, while those with spacing factors greater than 0.01 inches are poorly protected.

Finally, the authors point out that since the study was restricted to certain Indiana cherts and shales subjected to specific methods of test, the conclusions can logically be applied only to similar cherts and shales under similar conditions. However, in some cases, field behavior of the cherts and shales may be inferred from the conclusions.

DEGRADATION OF AGGREGATES

In connection with an investigation currently underway in the School of Civil Engineering at Purdue University, Aughenbaugh, Johnson and Yoder (17) made a critical review of the information available from research on aggregate degradation. The following is their summary and conclusions on the subject reached after studying over eighty published technical papers and unpublished reports from research laboratories in five countries. It is reproduced with permission of the authors.

<u>Summary</u>. Aggregate degradation has become a more important aspect of aggregate quality in recent years although it has been recognized since the turn of the century. Detrimental breakdown of aggregate pieces has been more of a problem in bituminous construction where changes in the mix from design gradations can cause loss of stability, raveling, etc. As a result, most degradation investigations have been in this direction, although there has been intensive study of in-service degradation in base courses as well as bituminous mixes in the northwestern section of the United States. Outside of a few laboratory and field studies made by the New England Division, U. S. Corps of Engineers, there have been no investigations directed towards determining whether degradation causes some materials to become frost susceptible and only a few studies have been concerned with aggregate breakdown during construction. The research that has been done in this field concerns

surface treatments or application-type construction in which the thickness of the layer is equal to the diameter of the aggregate pieces.

Certain factors that affect degradation have been intensively studied and evaluated for their role or influence in the problem. Since much of the research has been directed toward specific problems and by necessity has had limited scope, the relative influence of the evaluated factors in other situations is not entirely known. This may account for the wide differences of opinion by many investigators on the effect of some factors. Several factors, which may possibly govern aggregate breakdown, have had little or no investigation. Consequently their relative values are not known. On the basis of present knowledge only two factors seem to be "prime" or governing factors in all phases of degradation. They are aggregate type and compactive effort.

A great deal of attention has been directed toward investigating existing or specially developed laboratory tests for appraising an aggregate's susceptibility to degrade. Some existing tests such as the Deval test have proven to be inadequate, whereas others, such as the Los Angeles abrasion test, have shown both good and anomolous results. Many of the existing tests have not been investigated fully although many opinions have been formed on their adequacy. The Los Angeles test has been modified several times and a few new tumbler tests have been developed to provide reliable and rapid testing. Some of these tests were found to be dependable and have been adopted as routine laboratory tests by various agencies. Their possible adaptability outside of the area for which they were developed and to situations other than those for which they were devised is not known. Petrographic analysis is probably the best evaluation for all phases of degradation but many investigators challenge its feasibility as a routine laboratory test.

A moderate amount of research has been conducted on the subject of beneficiation of aggregates known to be of poor degradation quality but used because of economic necessity.

Conclusions. The literature review indicates the following conclusions.

1. Degradation is a multi-phase phenomenon. It may or may not be detrimental for a given case depending upon the aggregate purpose. There are some cases where it will be beneficial.

2. There seems to be a regional correlation for catagorizing the type of degradation problems that can be expected. This developes mainly from the common problems experienced by the northwestern states.

3. Degradation should become an increasingly important problem in the future. This is due to two causes; a) recognition of the problem by investigators and, b) the increases in compactive effort and/or densities required, and in traffic volume and loads.

4. All the factors controlling degradation are not known or understood. The factors involved apparently are not the same for all cases. Investigation must be concentrated on revealing the principal governing factors. Reasons must be sought for the conflicting data that now exist.

5. Very little information is available on degradation in base courses or aggregate layers of significant thickness. There are even less data on the degradation that might occur during construction of these multi-aggregate thick layers.

6. No previous studies have been made on degradation which produces frost-susceptible base courses. An effort should be made to recognize the main factors involved in this type of aggregate breakdown. Once the governing factors are known, there should be an attempt to correlate this phase of degradation to other types in order to make full use of previous investigators' findings.

7. More study is needed to insure the adoption of adequate physical laboratory tests. Several physical tests (mostly tumbler tests) are now being used to evaluate an aggregate's susceptibility to degradation. These tests should be investigated for their reliability in evaluating degradation in other regions where different factors may govern. Several different physical tests may have to be used to adequately cover all phases of degradation.

CHEMICAL REACTIONS OF AGGREGATE IN PORTLAND CEMENT CONCRETE

Chemical reactions of aggregates in concrete can have a significant effect on the concrete's performance. In the United States the detrimental reaction that has received the most attention in recent years is the alkali-aggregate reaction. This was first reported by T. E. Stanton (18) in 1940 as the cause of deterioration of certain concretes in California and has since been reported in seventeen states. The damage to the concrete results from an expansive reaction between the alkalies (sodium and potassium compounds) in the cement and certain siliceous constituents of the aggregate.

A great deal of research has been done on this subject and much has been written about it. In 1958, Committee B-2 of the Highway Research Board published a report (19), compiled and written to provide information concerning, a) the locations where the reaction has occurred, b) the laboratory techniques that have been developed to identify potentially reactive aggregates, and c) measures that should be taken when these aggregates are used in concrete. This is an excellent report, prepared by a group of engineers, geologists and chemists who have had wide experience with the problem. It provides a concise summary of the state of knowledge on the problem as of 1958.

According to Mielenz (20), the most important deleteriously alkali-reactive rocks are opaline cherts, chalcedonic cherts, quartzose cherts, siliceous limestones, siliceous dolomites, rhyobites and tuffs, docites and tuffs, andesites and tuffs, siliceous shales, phyllites, siliceous slates, opaline concretions, fractured, strained and inclusion-filled quartz and quartzites. Opal is the most alkali-reactive of all minerals.

A suggested mechanism for the reaction was given by Powers and Steinour (21). Mather (22) summarized their hypothesis as follows:

> "Amorphous silica has structural discontinuities that lead to surface reaction with alkalies to yield an alkali-silica product when lime is unable to diffuse to the reaction site fast enough to form the lime-alkali-silica product. Expansion occurs when the alkali-silica product imbibes water. The alkali-silica product will not form when the silica particle is sufficiently small or the ratio of absorbed lime to alkali in the layer of reaction product is sufficiently high, the ratio being a function of alkali content of the external solution. Hence, excessive expansion occurs when the amount of reactive constituent and its particle size, and the amount of alkali in the cement, interact in a favorable environment to produce the alkali-silica reaction product and it, in turn, imbibes water."

Several investigators have suggested that unless a cement contained at least 0.6 percent alkali (expressed as sodium oxide equivalent), detrimental expansion of concrete would not take place. Powers and Steinour point out that published experimental data on laboratory specimens containing reactive aggregate show that the cement can contain some alkali without developing expansion from the alkali-aggregate reaction, but that the safe amount of alkali is not necessarily 0.6%; it depends on the amount of reactive mineral present and the size of the reactive particles.

Two tests to determine the potential alkali reactivity of concrete aggregates have been standardized by the American Society for Testing and Materials. These are C 227, Test for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method) (Tentative), and C 289, Test for Potential Reactivity of Aggregates (Chemical Method) (Tentative). The mortar bar expansion test (C 227) is generally considered to be the most reliable method available, but its performance requires considerable time.

Method C 289, also known as the "quick chemical test", was developed in order to obtain a more rapid evaluation of concrete aggregates.

A comparison of the two methods was made by Chaiken and Halstead (23). Fifty-two concrete aggregates were evaluated by means of both tests. Some of their conclusions were:

"The chemical test for the potential reactivity of aggregates (ASTM C 289-57T) generally shows good correlation with the results obtained by mortar bar tests.

"Reliable results are not always obtained in the chemical test when certain carbonates or serpentine minerals are present. An empirical division of the chemical test results is proposed which would serve to isolate such interferences and thereby indicate which aggregates require further study. This procedure would eliminate the need for additional time-consuming tests on many satisfactory aggregates.

"Highly reactive aggregates may be classified as reactive in the chemical test and yet fail to produce mortar expansion. An additional empirical division of the chemical test results is suggested which would serve to identify such aggregates. It is believed that many such aggregates may actually become dangerous in concrete if diluted with inert aggregates. The proposed division would focus attention upon those aggregates requiring special investigation.

"A modification of the ASTM main boundary line is proposed as part of the general criteria for chemical test results. The adjusted line conforms more realistically to available data."

When it is necessary to use deleteriously alkali-reactive aggregates for economic reasons, suitable practices, developed from laboratory tests, experimental projects and extensive field experience, can be followed to produce durable concrete. On this subject, HRB Special Report 31 (19) contains the following recommendations:

"Durable concrete can be produced when deleteriously alkali-reactive aggregates are used with a low-alkali cement or with a high-alkali cement in combination with an adequate amount of a suitable pozzolan known to control the expansion associated with the alkali-aggregate reaction, or a suitable blast-furnace slag. A low-alkali cement is one that contains 0.60 percent or less total alkalies as Na_2O calculated as follows:

(percent Na_2O) + (0.658 x percent K_2O). A pozzolan is a siliceous or siliceous and aliminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

.... "Sea water or other waters containing a significant quantity of alkali salts should not be used as mixing water where reactive aggregates are involved."

AGGREGATES AND SKID-RESISTANCE OF HIGHWAY PAVEMENT SURFACES

It has been estimated that skidding is a factor in over six percent of all traffic accidents in the United States. It is obvious from an examination of accident records that not all accidents involving some skidding are a direct result of slippery pavements, but it is never-the-less true that the incidence of total accidents, as well as accidents directly involving skidding, increases significantly as the coefficient of friction between the sliding tire and pavement surface decreases (24).

Research on skid-resistance of highway pavement surfaces has been conducted in many countries throughout the world. Some investigators have focused attention on the measurement of skid resistance, both in the laboratory and in the field. Others have worked with rubber formulations and tire designs or attempted to develop paving mixtures having the optimum texture to minimize skidding. Work has also been done to evaluate the part played by the aggregate. In this section a brief review is presented of some investigations made at Purdue concerning this aggregate factor. Professors Goetz, Lounsbury, Shupe and Stevens were the principal investigators in this work and the following summary is based on their published reports (25-31).

A necessary first step in laboratory research on pavement friction is the development of equipment and procedures for adequately evaluating the skidding resistance of a test specimen. The Purdue investigators developed instrumentation to meet the following requirements which they deemed essential for the proposed work:

1. The equipment should be adaptable both to specimens prepared in the laboratory and to samples removed from a highway surface.

2. Since the degree of wetness is significant, provision should be made to insure that the surface of the specimen is well lubricated during testing.

3. The type of rubber from which the testing shoe is made, the area of contact, and the normal pressure between the testing shoe and the surface of the specimen should be such that the degree of envelopment of the aggregate particles which occurs during braking of a passenger car on a highway surface is simulated.

4. In order to obtain a realistic evaluation, the relative speed between the surface and the testing shoe should be high. On the basis of previous field studies, a speed of 30 mph appeared to be a reasonable value.

5. The results should be relatively free from individual bias. To this end, automatic recording would be preferable to some method of dial or scale reading during testing.

6. In order to accomplish a large-scale program of research, the equipment should be rugged and capable of producing a large amount of reproducible data over a prolonged period of testing with a minimum of servicing, adjustment, and repair.

A complete description of the apparatus is given in (26). Basically the equipment measures and records the frictional force developed between a 6-inch diameter test specimen and a rubber testing shoe for a relative speed between the two sliding surfaces, at the mean radius of the area of contact, of approximately 30 mph. Laboratory results with the apparatus were correlated with field measurements of pavement friction (stopping-distance method) and good agreement was found (28).

Results of tests made with this laboratory device are expressed as Relative Resistance Values (RRV) since the machine, like most others of its kind, evaluates materials on a relative basis. It was decided that a value of 1.00 would be assigned to specimens of Kentucky rock asphalt, a native sandstone material, because highway surfaces paved with it consistently exhibit the best skidding resistance when wet. On this basis, appropriate calibration of the output analyzer was made so that, for all practical purposes, the scale of possible RRV's went from zero to 1.00. Examples of values on this scale were 0.66 for a bituminous concrete surface and 0.17 for an extremely slippery "bleeding" asphalt surface. Again, for emphasis, these are values relative to the performance of a "standard" - Kentucky rock asphalt. No effort was made to convert this reading to a coefficient of friction.

Once the measurement technique was developed and perfected it was used in several separate yet interrelated studies as the tool for the evaluation of many factors affecting pavement slipperiness. No attempt is made to detail or even outline the scope of these investigations but in the following paragraphs some of the most pertinent results and recommendations deriving therefrom are summarized. These statements are drawn principally from references 27 and 28.

1. If an excess of asphalt does not occur at the surface, dense-graded bituminous mixtures will exhibit somewhat better anti-skid characteristics than open-graded mixtures composed of identical aggregate. Dense-graded mixtures exhibit a greater tendency toward "bleeding," due to the additional compaction of traffic, than open-graded mixtures; but

if this contingency is adequately considered in the design of the mixture, the dense-graded surfaces, by furnishing a greater uniformity of friction-transfer over the entire contact area between the tire and surface, provide somewhat greater skid-resistance than pavements containing surface voids of appreciable individual size. In addition, an open-graded surface exposes the aggregate to greater envelopment by the tire and to a higher polishing effort than a dense-graded surface.

2. Since surfaces containing crushed aggregate possess better initial skid-resistance than pavements made from rounded aggregates of the same composition, there is some justification, based on skid-resistance alone, for requiring that any naturally-rounded coarse aggregate be entirely crushed if it is to be used in the pavement surface. After an appreciable period of wear, however, the skid-resistance of the two surfaces will be nearly identical.

3. The polishing characteristics of aggregates will be similar both in portland cement and in bituminous mixtures which are composed entirely of one aggregate type. However, it will usually require a greater wearing effort to polish the aggregate and to arrive at the ultimate slippery condition with portland cement concrete as compared to bituminous surfaces.

4. There are certain limestones which should not constitute the total surface aggregate in bituminous pavements. Results of the initial laboratory study indicate that uniform fine-grained or oolitic limestones, consisting essentially of pure calcium carbonate, fall in this category. Surfaces of this nature possess only fair skid-resistance when new, and may become dangerously slippery after a moderate amount of traffic wear.

Other types of limestones, such as the highly-dolomitic Indiana limestone, may be entirely satisfactory as the total surface aggregate for bituminous pavements if severe traffic conditions are not anticipated. Surfaces composed of these more-resistant limestones may ultimately polish; and, if traffic is extreme, can do so in a relatively short period. However, this same observation also can be made for pavements constructed with such aggregates as the fine-grained basalts, chert, and high-quartz gravel. These relatively polish-resistant aggregates may retain a certain degree of their initial angularity for an appreciable period, but due to the uniform nature of wear of the fine-grained structure, can ultimately polish excessively.

5. In order for a pavement surface, constructed either with portland cement or bituminous materials, to retain a non-skid surface under prolonged action of heavy traffic, some type of differential wear of the surface components is essential, since a uniformly-polished surface will be dangerously slippery when wet. For portland cement concrete, this differential wear may occur due to the variation in resistance to wear of the cement paste and the fine and coarse aggregate. For both portland cement and bituminous surfaces an aggregate, such as sandstone or some varieties of granite for which a coarse particle-by-particle type of wear occurs, may contribute to excellent skid-resistance. Similarly the differential wear that takes place with Kentucky rock asphalt or a silica-sand surface treatment, due to ejection of aggregate particles from the pavement surface by traffic, results in a "non-skid" pavement.

6. Blending of a polish-resistant fine aggregate to improve the anti-skid characteristics of a polish-susceptible limestone is, at best,

only moderately successful with bituminous mixtures. The laboratory investigation indicated that an appreciable quantity of a harsh material, such as silica sand, was required to increase the skid-resistance to a reasonable value. This quantity of silica sand probably could be used much more effectively as a non-skid surface treatment. Frequently the nature of wear of a bituminous highway surface is such that the fine-aggregate and asphalt matrix erodes away, and the area of contact between the tire and pavement consists almost entirely of coarse aggregate. For such a condition, the blending of skid-resistant fine material results in little improvement in the anti-skid characteristics of the mixture.

7. Blending of a polish-resistant fine aggregate to improve the anti-skid characteristics of a polish-susceptible limestone in portland cement concrete is much more effective than with bituminous mixtures. The fine-aggregate mortar makes an important contribution to the skid-resistance developed by portland cement concrete, even after wear has progressed to the point where appreciable amounts of coarse aggregate are exposed. Laboratory results indicate that the use of a harsh, resistant fine aggregate with a polish-susceptible limestone coarse-aggregate will usually result in good skid-resistance of the mixture, while even a naturally-rounded sand will promote sufficient differential wear to develop adequate skid-resistance.

8. Limestone should not be used as the total aggregate in portland cement concrete pavements. If the cement paste, the fine-aggregate of the mortar, and the coarse aggregate all possess essentially the same resistance to wear, a uniformly-polished surface may result that is dangerously slippery when wet.

9. A non-skid silica-sand surface treatment, such as that developed by Virginia (32), probably holds the best promise of being generally accepted as an effective means of combating pavement slipperiness. The continuous rejuvenation of the surface, which accompanies the particle-by-particle type of wear, results in excellent anti-skid characteristics during the entire life of the treatment. Such non-skid surface treatments, when placed on existing slippery pavements that are structurally adequate or used as a preventive measure in new construction with polish-susceptible aggregates, can make a significant contribution to driving safety.

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